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Infinite uncertainty, forgotten feedbacks, and cost-benefit analysis of climate policy

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Abstract Tol (2003) questioned the applicability of expected cost-benefit analysis to global mitigation policy when he found evidence that the uncertainty surrounding estimates of the marginal damage of climate change could be infinite even if total damages were finite. Yohe (2003) suggested that this problem could be alleviated if international development aid were directed at eliminating the source of the problem – climate induced negative growth rates in a few regions along a handful of troublesome scenarios. The hypothesis about adding a second policy lever to the climate policy calculus is shown to hold, though perhaps not as robustly as originally thought. A portfolio of international policies with at least two independent tools can avoid infinite uncertainty on the margins and the associated implications for global mitigation policy at a reasonable price even in the relatively unlikely event that climate change causes negative economic growth in a region or two.

1 Introduction

The determination of appropriate climate policy is controversial because it is driven, at least in part, by the choice of a decision-making framework. This choice, in turn, depends on

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alternative views of not only how the world should work, but also how it actually *does* work. Two alternative approaches dominate the discussion. The first is based on (expected) cost-benefit analysis. Broadly defined, this approach can include risk management techniques by which the negative influences of variance in state variables can be accommodated within the decision-making criteria; see, for example, Yohe et al. (2004). The second defines tolerable windows of climate change. It is a variant of safe minimum standards which function as thresholds for impacts that are to be avoided almost at any cost; see, for example Bruckner et al. (2003) and Tol and Yohe (2006).

As argued in Pratt et al. (1995), however, it is axiomatic that cost-benefit analysis can be applied to a policy decision only when uncertainty about net benefits is finite.[1] If this condition cannot be satisfied, then cost-benefit analysis is completely invalid and the decision-maker should turn to perspectives designed to minimize the maximum regret assigned across a wide range of plausible futures. The decision-maker, in other words, should ask analysts to determine safe minimum standards or windows of tolerable impacts. It follows, therefore, that the discussion on how to approach the climate policy debate turns in large measure on the size of the uncertainty.

Tol (2003) used the *FUND* integrated assessment model to explore the range of uncertainty in estimates of the marginal damage costs of carbon dioxide emissions, a crucial input into any expected cost-benefit analysis of greenhouse gas emissions control. He found evidence that this uncertainty could become infinite even if total damages were, themselves, finite. His reasoning contemplated a philosopher-queen who would take account of how climate change impacts all people. Indeed, she would design her climate policy on the basis of monetised impacts that were aggregated across the globe using equity-weights that explicitly recognized the fact that an extra dollar of income would be worth more to a poor man than it would be to a rich man. She was, as well, aware that economic growth could be reversed in some countries under some not-implausible specifications of climate change and associated damages. As a result, she assigned these countries negative consumption discount rates and high equity-weights in her aggregation scheme so that these extreme scenarios ultimately overwhelmed the expected value of the marginal damage costs, its standard deviation, and her calculation of the optimal policy. Without equity weights, she could ignore the low dollar value of climate change damages to the world's poorest countries in her global calculus; but with equity weights, negative economic growth rates would define impacts thresholds that would serve, for all intents and purposes, as binding boundaries of tolerable climate change. See Azar and Lindgren (2003) and Howarth (2003) for further commentary.

Yohe (2003) responded to Tol's reasoning by arguing that global policy makers, or Tol's philosopher-queen for that matter, would not be restricted to one policy lever (mitigating greenhouse gas emissions) in these circumstances. He hypothesized, in fact, that the global community would find it in its own best interest to offer economic aid to poor countries. If this aid prevented negative economic growth in some countries, then they could impose less stringent climate policy upon themselves. The problem highlighted by Tol was, in his eyes, simply a problem of trying to confront two policy objectives (optimal intervention into anthropogenic forcing of the climate system and maintaining positive economic growth worldwide) with only one policy tool (climate policy).

[1]See Persky (2001) for a further discussion of cost-benefit analysis, particularly the strict utilitarian welfare assumptions. Equity and cost-benefit analysis in the context of climate change are discussed, amongst others, by Kavuncu and Knabb (2005; see also Gerlagh 2006) and Tol (2002a).

In this short paper, we test this hypothesis by including an economic aid feedback mechanism that would be triggered by catastrophic climate impacts and thus insure that the variance of marginal damages is finite. Before we describe some of the details of the numerical modelling environment in Section 3 (it has evolved since 2003), we offer a brief sketch of its conceptual framework in Section 2. Section 4 subsequently records the results of a Monte Carlo analysis of the marginal damage costs of carbon dioxide, and Section 5 offers some concluding remarks. The bottom line is qualified support for Yohe's (2003) hypothesis.

2 The analytical context

For the sake of constructing the simplest context within which to explore the sources of the philosopher-queen's possible conundrum, assume that that per capita income y in country c follows a growth path of the form

$$y_{c,t} = \left[1 + g_{c,t} - f\left(\frac{D_{c,t}}{Y_{c,t}}\right) + h\left(\frac{A_{c,t}}{Y_{c,t}}\right)\right] y_{c,t-1} \tag{1}$$

where D is the damage of climate change, Y is GDP, A is the aid received, and g is the growth rate in absence of climate change and international aid; the subscripts c and t index specific countries and specific time periods, respectively. The function f relates the (negative) impacts of climate change (as a fraction of GDP) on economic growth; it is described in some detail Fankhauser and Tol (2005). For present purposes, it is sufficient to note that climate damages are generally thought to be larger, as a percentage of GDP, in poorer countries than rich ones (because adaptive capacity is lower, health care is worse, the proportion of GDP related to the agriculture sector is larger, etc.). Meanwhile, the function h relates the (positive) effects of international aid on economic growth; Easterly (2002) offers a summary of the literature supporting its inclusion in Eq. 1. Finally, let $f(0)=h(0)=0$.

If we also assume that our philosopher-queen is a Benthamite utilitarian (Fankhauser et al. 1997), then marginal damage cost MD of carbon dioxide emissions at time s is the discounted sum of contemporaneous marginal damages from period s forward. Notationally,

$$MD_s = \sum_{t=s}^{\infty} \sum_{c=1}^{C} R_{c,s,t} D_{E_s;c,t} \left({\tilde{y}_t}/{y_{c,t}} \right)^{\eta} \tag{2}$$

where D_E is the contemporaneous marginal damage

$$D_{E_s;c,t} = \frac{\partial D_{c,t}}{\partial E_s} \tag{3}$$

and $\tilde{y}$ is the average per capita income in the world. The parameter η is the consumption elasticity of marginal utility for a utility function of the form

$$U_{c,t} = \frac{y_{c,t}^{1-\eta}}{1-\eta}. \tag{4}$$

In the simulation work, though, we assume that $\eta=1$ so that

$$U_{c,t} = \ln\left(y_{c,t}\right). \tag{4a}$$

The last term in Eq. 2 represents the equity weighting scheme designed to reflect variation in the welfare value of the marginal dollar across different countries (rich and poor). It is low less than one for rich countries whose per capita incomes are above the global average, and it is above one for poor counties whose per capita incomes are below the global average. Meanwhile, R is the discount factor; it takes the form

$$R_{c,s,t} = \prod_{r=s}^{t} \left\{1 + \rho + \eta\left[g_{c,t} - f\left(D_{c,t}\right) + h\left(A_{c,t}\right)\right]\right\}^{-1} \tag{5}$$

where ρ is the pure rate of time preference.

With this notation in hand, the mechanisms sketched in the introduction are clear. We have already noted how a country with a low per capita income would have a high equity weight in Eq. 2 unless η=0. Of course, monetary damages D_c in such a country would, in absolute terms, be small over time; but we have already argued that $f(D/Y)$ would then be high. It follows that Eq. 5 identifies a second reason why the contribution of a poor country with small absolute damages recorded directly into Eq. 2 could nonetheless be quite large. Even small absolute damages can be a large fraction of GDP in a poor country; as a result, small absolute damages in a poor country can make the denominator of the discount rate be smaller than it would be otherwise and perhaps even drive it below one.

Other terms in the Ramsey discounting depicted in Eq. 5 could enlarge its contribution even more by making it even more likely that the discounting denominator was less than one. To see how, think about a country where climate impacts work to slow economic growth; the denominator would shrink. If those impacts were so strong that growth turned negative, though, then the discount rate could easily turn negative (at least absent economic aid and especially if the pure rate of time preference imposed on intergenerational decisions is small or perhaps even equal to zero).

Finally, the basis of our exploration of Yohe's (2003) hypothesis can also be found in Eq. 5; international aid, working through function h, is the only lever with which the philosopher-queen could fight these effects. Tol (2003) did not allow international aid, so A=0 throughout that earlier analysis. Here, we allow A>0 so that, in principle, we have a mechanism to offset the negative impact of climate change on growth.

In the analysis described throughout this paper, we assume a fixed savings' rate. That is, g is independent of $f(D/Y)$ in Eq. 1. Relaxing this assumption would provide an additional mechanism to avoid the negative impacts of climate change on economic growth, but we will show below that international aid may be sufficient and that is enough to make our point. Besides, if confronted with inevitable economic collapse in the future, people may decide to increase consumption rather than investment, and this tendency would be greater if it would trigger international aid. Adding an international capital market to the modelling exercise would further complicate the analysis. Foreign direct investment may well reduce the probability of economic collapse in the face of severe climate impacts, but it is not difficult to tell a story in which capital flight from those severe impacts would accelerate an economic decline. Including either of these complications would require major changes to the model that we employed, and so they are postponed (without undermining our two objective – two policy exploration) to future research.

3 The model

This paper uses version 2.8 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 2.8 of *FUND* corresponds to version 1.6, described and applied by Tol (1999, 2001, 2002a), except for the impact module, which is described by Tol (2002b,c) and updated by Link and Tol (2004). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. Finally, the model considers emission reduction of methane and nitrous oxide as well as carbon dioxide, as described by Tol (2006a). A full list of papers, the source code and the technical documentation for the model can be found online at http://www.fnu.zmaw.de/FUND.5679.0.html. Readers familiar with *FUND* can skip to Section 4 without loosing any continuity in our argument.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. The model runs from 1950 to 2300 in time steps of 1 year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The twenty-second and twenty-third centuries are included to account for the fact that key impacts of a weakening or a shutdown of the thermohaline circulation would be disregarded if the time horizon of the simulations were shorter. Previous versions of the model stopped at 2200.

The period of 1950–1990 is used for the calibration of the model, which is based on the *IMAGE* 100-year database (Batjes and Goldewijk 1994). The period 1990–2000 is based on observations (WRI 2000). The climate scenarios for the period 2010–2100 are based on the EMF14 Standardized Scenario, which lies somewhere in between IS92a and IS92f (Leggett et al. 1992). The 2000–2010 period is interpolated from the immediate past, and the period 2100–2300 extrapolated. The economic scenario is in market exchange rates (see Nordhaus 2007; Tol 2006b).

The scenarios are defined by the rates of population growth, economic growth, autonomous energy efficiency improvements as well as the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide. The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (WRI 2000). It is extrapolated based on the statistical relationship between urbanization and per-capita income, which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. As a result, climate change reduces long-term economic growth, although consumption is particularly affected in the short-term. Economic growth is also reduced by carbon dioxide abatement measures. The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies, an option not considered in this paper.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change. Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted. The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is represented by the five-box model of Maier-Reimer and Hasselmann (1987). Its parameters are taken from Hammitt et al. (1992). The model also contains sulphur emissions (Tol 2006a).

The radiative forcing of carbon dioxide, methane, nitrous oxide and sulphur aerosols is determined based on Shine et al. (1990). The global mean temperature T is governed by a geometric build-up to its equilibrium (determined by the radiative forcing RF), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents. Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn et al. 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg et al. (1996).

The climate impact module, based on Tol (2002b,c) includes the following categories: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhoea, energy consumption, water resources, and unmanaged ecosystems. Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/year) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol 2002c).

People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline 1992). The value of emigration is set to be 3 times the per capita income (Tol 1995, 1996), the value of immigration is 40 per cent of the per capita income in the host region (Cline 1992). Losses of dryland and wetlands due to sea level rise are modelled explicitly. The monetary value of a loss of one square kilometre of dryland was on average \$4 million in OECD countries in 1990 (cf. Fankhauser 1994). Dryland value is assumed to be proportional to GDP per square kilometre. Wetland losses are valued at \$2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their 'natural' units (cf. Tol 2002b). Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum, which is determined by a variety of factors, including plant physiology and the behaviour of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol 2002c).

The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, diarrhoea malaria, dengue fever, and schistosomiasis are modelled as simple power functions. Impacts are either negative or positive, and they do not change sign (cf. Tol 2002c).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol 2002c).

4 Results

FUND was exercised to explore the distributions of marginal damages with and without an aid policy that would transfer up to 1 or 2% of the combined GDP of the OECD as necessary to sustain economic activity in regions who experience the unlikely event that climate impacts would otherwise drive them to subsistence levels (i.e., the marginal damage of climate change would become unbounded for these regions). Such transfers are triggered as soon as per capita income starts to fall in any region that is currently not in the OECD, and OECD regions are assumed to contribute to the transfers proportional to their GDP. These transfers are assumed to exactly offset the income fall, unless the total transfers exceed 1 (or 2%) of the total GDP of the OECD regions. It is important to note, for context, that OECD countries aim to give 0.7% of their GDP in official development aid; of course, few countries actually meet this target.

Two different regional weighting schemes in the global objective function were also considered. In the first, individuals' utilities around the world were simply summed in the calculation of a Benthamite metric of global welfare. In the second, individuals' utilities were assigned "equity weights" according to Fankhauser et al. (1997). In all cases, though, regional utilities were discounted according to the Ramsey rule given globally consistent pure rates of time preference but regionally specific and endogenously determined rates of growth in per-capita consumption. Slow or negative growth rates caused by particularly pernicious climate change could therefore receive abnormally high weights in the global policy analysis.

Table 1 displays results drawn from Monte Carlo analyses of 50,000 runs with and without aid. The assumptions on the probability density functions of the parameters can be found at http://www.fnu.zmaw.de/FUND.5679.0.html. The various panels of the table

Table 1 Characteristics of the marginal damage costs of carbon dioxide emissions (in dollars per tonne of carbon) without and with aid (capped at 1 or 2% of OECD income) in a Monte Carlo analysis with 50,000 runs

Pure rate of time preference:		0%	0%	1%	1%	3%	3%
		Simple sum	Equity weights	Simple sum	Equity weights	Simple sum	Equity weights
No aid	Mean	226.6	12,523.4	36.7	790.0	1.3	8.9
	St. dev.	3,001.8	313,576.8	199.3	17,444.4	20.8	75.9
Percentiles:	1%	−214.2	−366.7	−41.8	−47.2	−21.8	−29.3
	5%	−58.1	−53.2	−27.8	−29.9	−16.8	−22.0
	50%	56.1	112.1	8.5	21.4	−4.0	−2.7
	95%	732.7	11,464.3	180.4	928.5	37.0	69.8
	99%	2,374.0	185,468.5	403.6	12,077.3	88.5	191.3
Aid, 1% max	Mean	94.8	192.5	28.1	48.3	1.2	5.4
	St. dev.	8,296.6	15,733.7	510.0	958.6	20.7	32.3
Percentiles:	1%	−277.0	−302.8	−42.2	−45.8	−21.8	−29.4
	5%	−61.0	−52.4	−27.9	−29.7	−16.8	−22.0
	50%	53.0	99.6	8.1	19.4	−4.0	−2.8
	95%	551.9	978.4	163.8	239.9	36.7	59.9
	99%	1,259.5	2,639.9	317.0	489.1	87.7	137.8
Aid, 2% max	Mean	129.8	254.6	30.2	52.0	1.2	5.4
	St. dev.	914.5	1,466.5	89.1	136.9	20.6	32.1
Percentiles:	1%	−280.6	−303.4	−42.2	−45.8	−21.8	−29.4
	5%	−61.1	−52.2	−27.9	−29.7	−16.8	−22.0
	50%	52.9	99.6	8.1	19.4	−4.0	−2.8
	95%	548.1	968.5	163.5	239.8	36.7	59.9
	99%	1,247.3	2,486.4	315.9	482.1	87.7	137.7

reflect characteristics of the distribution of the marginal damage of carbon emissions (in dollars per tonne of carbon) across the runs for three different specifications of the pure rate of time preference and two different utility weighting schemes. Notice that adding aid to the policy calculus always lowers the mean and median estimate of marginal damage as well as its variance. These reductions are, though, always larger for the equity weighting cases and for cases in which the social discount rate is diminished by smaller pure rates of time preference. Indeed, the reductions can be several orders of magnitude in those cases. Moreover, while increased aid always reduces the variance (reflected by standard deviation in Table 1) of marginal damages, it need not reduce the mean (or the median) for low discount rates even for the equity weighting calculations.

These trends are easily explained in terms of the relative importance associated with the occasional regionally catastrophic scenario in the expected value calculation. Equity weights accentuate these cases in this calculation, and so the expected value calculus assigns significant value to economic aid that can work to reduce the severe harm caused by carbon emissions, which bring countries close to their critical margins. By way of contrast, the expected value calculus also assigns ordinary (more modest) value to economic aid that can work to reduce the modest harm caused by carbon emissions elsewhere. Low discount rates (i.e., those associated with low pure rates of time preference) operate in the same way but without regard to geographic differentiation, and so their effect is smaller. Specifically, lower pure rates of time preference expand the weight given to damage in the distant future when regional catastrophes may occur. Higher rates, of course, do the opposite. Finally, the effect of increasing aid from 1 to 2% can be explained in terms of the overall economic productivity of the transfer. The reduction in global economic growth associated over time with the second 1% increment does not reduce climate damage as effectively as the first 1%, and this lost power counts more heavily for smaller discount rates. Besides, more aid would sustain a vulnerable economy, increasing aggregate damages.

Figures 1, 2, and 3 offers some insight into why the variance of marginal damages does not necessarily converge as more runs are added to the analysis, though the problem is more severe for equity weighting (Figs. 1 and 2). The sudden peaks that appear along the "No Aid" and "Aid, 1%" schedules in Figs. 1 and 3 indicate the occurrence of scenarios for which high marginal damages are felt in some region of the world. Figure 1, for example, shows that a run just before the 15,000th for the "Aid 1%" simulations and another just before the 40,000th run for the "No Aid" simulations cause such a peak given a 1% pure rate of time. Interestingly, Fig. 1 shows that allowing aid to climb to 2% of GDP in the OECD countries eliminates the importance of both peaks; moreover, aid from the OECD limited to 1% of GDP seems to eliminate the significance of the second and higher peak. These regionally confined economic catastrophes are rare events in the Monte Carlo simulations, but their occurrence in a poor but populated region gives them high weight in the expected value calculus from which estimates of marginal damages emerge when aid cannot fully compensate and/or when the pure rate of time preference is low. Indeed, a little bit of aid can bring a region back from the brink of catastrophe (and nearly unbounded marginal damages) without moving the region away from the region of high and steeply rising damages. In these cases, significant amounts of aid are required to reduce significantly the distribution of marginal damages. It was to be expected, therefore, that the variance would converge more robustly for the high-aid and/or high discount rate scenarios. Notice in Fig. 2, in fact, that the differences are muted by the higher discount rate associated with a pure rate

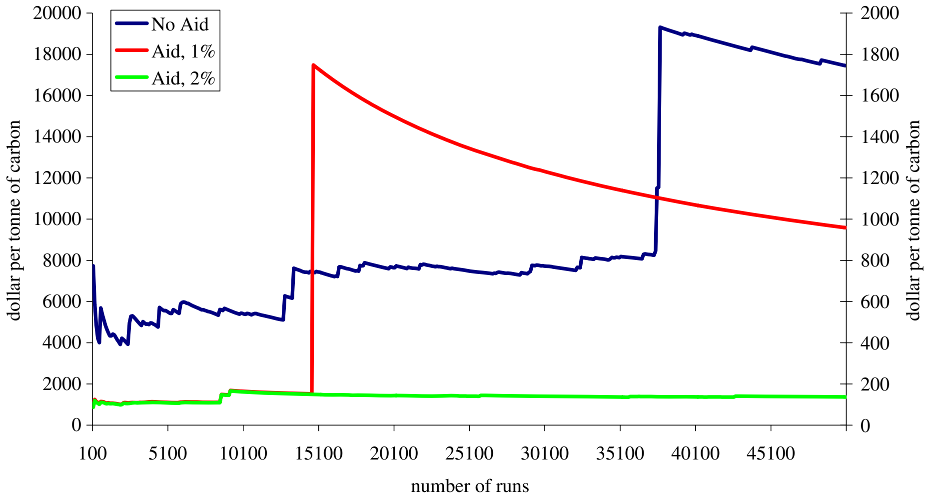

Fig. 1 The standard deviation of the marginal damage costs of carbon dioxide emissions with and without aid as a function of the number of Monte Carlo runs for a 1% pure rate of time preference; impacts are equity-weighted; annual aid is limited to 1 or 2% of OECD GDP. The "No Aid" estimates are measured against the *left-hand vertical axis*; the 1 and 2% Aid cases are calibrated by the *right-hand vertical axis*

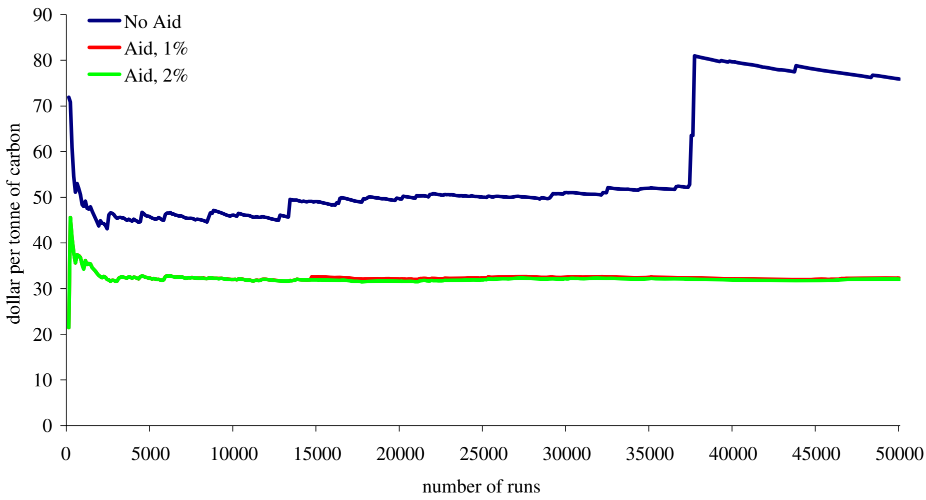

Fig. 2 The standard deviation of the marginal damage costs of carbon dioxide emissions with and without aid as a function of the number of Monte Carlo runs for a 3% pure rate of time preference; impacts are equity-weighted; annual aid is limited to 1 or 2% of OECD GDP

of time preference of 3%. In fact, aid eliminates both peaks for the high discount rate even with equity weighting, even if aid is limited to 1% of OECD income.

Figure 3 shows that, without equity weighing, aid may increase the variance. This is because, without equity weighing, the climate change impact on a collapsed economy would hardly count; a little aid would sustain such an economy and increase the absolute impacts it suffers. Figure 3 also shows that, if aid were higher, impacts would be lower; this is because a more robust economy would be less vulnerable to climate change.

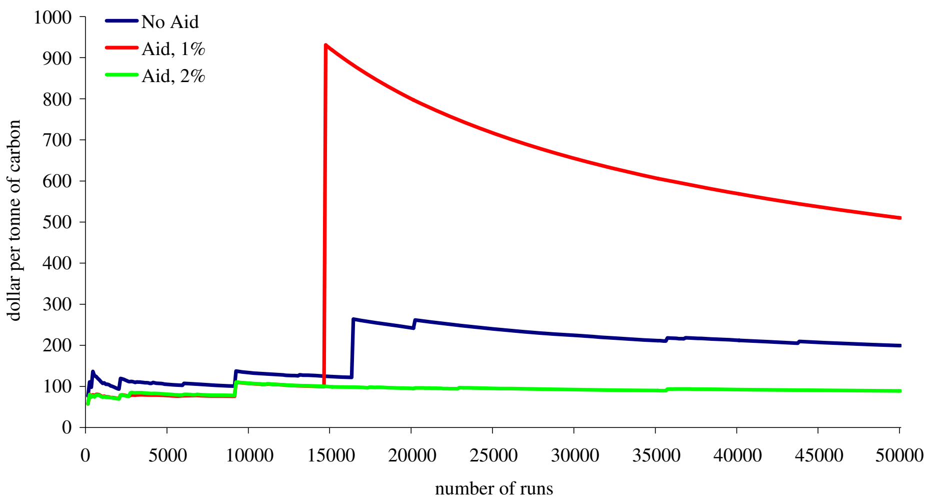

Fig. 3 The standard deviation of the marginal damage costs of carbon dioxide emissions with and without aid as a function of the number of Monte Carlo runs for a 1% pure rate of time preference; impacts are not equity-weighted; annual aid is limited to 1 or 2% of OECD GDP

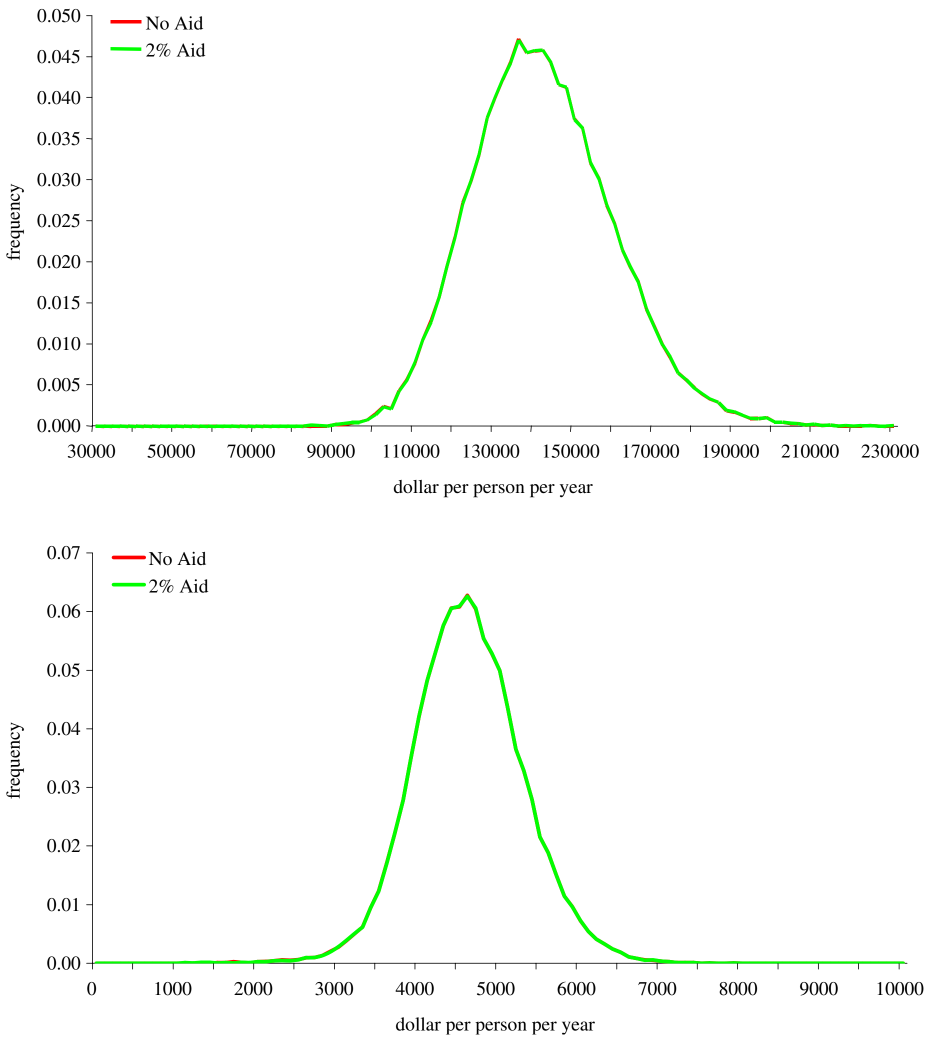

Fig. 4 Probability density function of the 2100 per capita income without aid and with (capped at 2% of OECD GDP) in the USA (*top panel*) and in Africa (*bottom panel*). Note that the lines overlap, that is, aid hardly affects the probability density function of per capita income

Figure 4 offers a different view of the results. There, the effects of aid are expressed as the difference in per-capita income between the United States and Sub-Saharan Africa (chosen to typify a high and a low income region, respectively). Notice that aid, even at a maximum of 2% of OECD GDP, has hardly any effect on the overall probability density of per capita income in 2100.

Figure 5 shows the probability density function of the *difference* in per capita income for the same two regions. Aid affects United States income in only 1.01% of the cases and African income in only 0.19% of the cases. This confirms the message from Fig. 4. The USA is more often affected than is Sub-Saharan Africa because other poor regions may face climate-change-induced economic collapse as well. In the 50,000 Monte Carlo runs, aid never reduces US income in 2100 by more than 10%; in this scenario, annual aid is capped

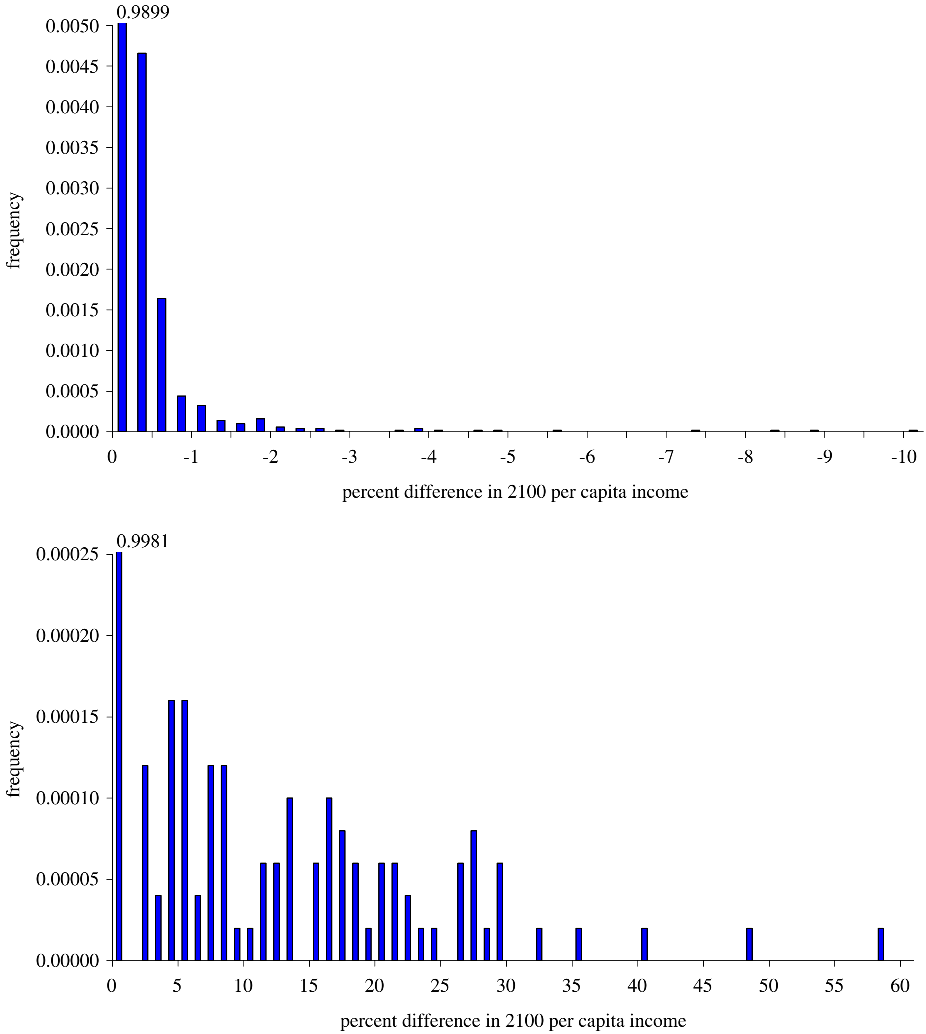

Fig. 5 Probability density function of the difference in the 2100 per capita income due to aid (capped at 2% of OECD GDP), expressed as a percentage of the same income without aid, for the USA (*top panel*) and Africa (*bottom panel*)

at 2% of GDP, but there are economic growth effects as well. On the other hand, per capita income in Sub-Saharan Africa can be up to 60% higher due to aid; in most cases, however, income is boosted by less than 30%.

5 Discussion and conclusion

It would appear that the hypothesis about adding a second policy lever to the climate policy calculus holds, but not as robustly as one might have thought initially. The vagaries of growth discounting, compounded here by equity weighting in the global welfare calculations, are always difficult to predict. Nonetheless, adding aid to the policy portfolio does reduce expected marginal damages associated with climate change, sometimes by orders of magnitude (for equity weighting and low pure rates of time preference). Aid also reduces the variance of marginal damages, again by orders of magnitude in some cases. These improvements can, though, be muted by high discount rates derived from high pure rates of time preference. Of course, the problem of large, maybe infinite variances is much less pronounced when discount rates are high. It is also possible to "do too much aid," particularly with a low discount rate and no equity weighting; but this is an unlikely combination. In short, a portfolio of international policies with at least two independent tools can avoid infinite uncertainty on the margins and the associated implications for global mitigation policy at a reasonable price even in the relatively unlikely event that climate change causes negative economic growth in a region or two.

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